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Weldability of Rare-Earth-Treated Homogeneous Armor Steel Plate
Final Report

Contract No. DA-36-034-ORD-1423RD

July 31, 1957 Major Report No. 207B

RESEARCH AND DEVELOPMENT DEPARTMENT

AMERICAN CAR AND FOUNDRY DIVISION
acf INDUSTRIES
INCORPORATED
30 CHURCH STREET NEW YORK

FORM 62-A

American Car and Foundry Division
ACF Industries, Incorporated
Research & Development Department

Weldability of Rare-Earth-Treated Homogeneous Armor Steel Plate
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by
George Reed

Approved by: J. M. Gruitch

FINAL REPORT

Contractor:	American Car and Foundry Division ACF Industries, Incorporated
Contract Number:	DA-36-034-ORD-1423RD
Title of Report:	Weldability of Rare-Earth-Treated Homogeneous Armor Steel Plate. Final Report.
File Number:	WAL 642/218-2
Date:	July 31, 1957
Agency:	Army Ordnance Department, Watertown Arsenal
Technical Supervision:	Watertown Arsenal Laboratory
Ordnance District:	Philadelphia
Author:	George Reed

Object: To determine the relative weldability of rare-earth-metal-treated, rare-earth-oxide-treated, and normal production manganese-molybdenum composition wrought homogeneous armor steels.

Summary: This report summarizes the results of the preparation of a series of test plates (Interim Report No. 1) made from each of the three armors, the laboratory study of the base materials and the welded joints (Interim Report No. 2), and the explosion bulge and ballistic testing carried out at Aberdeen (Armor Test Report AD-1241).

The comparative performance of the armor steels has been evaluated in each of the phases of the investigation and an attempt hus been made to correlate the results to determine the relative weldability of the materials.

Conclusions: No one of the three steels possessed superior weldability characteristics but, on a comparison basis, the rare-earth-oxide-treated heat had the best weldability and the production armor heat the poorest. The rare-earth-oxide-treated heat also possessed the lowest hardenability, a factor not believed to have been influenced by the rare-earth addition, and thereby had a better inherent weldability.

With regard to the effects of the rare-earth additions on the mechanical properties of the unwelded armor, it was indicated, though not proven, that the rare-earth-metal addition significantly reduced the sulfur content of the steel and improved the impact resistance. The rare-earth-oxide addition, on the other hand, appeared to have no significant effects on either sulfur content or impact resistance. Neither of the rare-earth additions appeared to have deleterious effects.

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Introduction

1. In the past, 1/2-inch thick wrought Army-type homogeneous armor plate has exhibited a tendency for low or borderline toughness qualities. The projectile-through-plate test was used as a measure of plate material toughness under former armor Specifications AXS 495, 57-115-11 and 57-115-11, Amendment 1, and, in the test, excessive exit diameters resulted unless material toughness was maintained at the maximum obtainable while the hardness was at a minimum commensurate with penetration requirements.

2. Later, Specifications 57-115-11, Amendment 2, and MIL-A-12560 (ORD) omitted the projectile-through-plate test and substituted the Charpy V-notch impact test as a measure of material toughness. Such a significant percentage of 1/2-inch armor failed to meet the specified impact resistance requirement that during the Korean crisis it was necessary to issue Engineering Change Order 35140, dated January 23, 1952, lowering the minimum Charpy V-notch impact resistance requirements by 3 foot-pounds so that sufficient acceptable 1/2-inch armor could be produced to maintain armored vehicle production schedules.

3. In an effort to overcome the tendency for low toughness, rare-earth additions have been made to a number of experimental and production heats. In some instances the impact resistance was improved but in others there was no improvement. The variation in effects apparently was due to the type of additions made, the method of making the additions and the amount of rare-earth elements retained. The use of production heats of rare-earth-treated armor in welded ordnance vehicles resulted in claims by some fabricators that the additions adversely affected weldability. These claims caused the Ordnance Advisory Committee on the Welding of Armor to request an investigation of the physical and weldability characteristics of rare-earth-treated wrought homogeneous armor steel. The investigation was undertaken by the Watertown Arsenal Laboratory and a portion of the over-all study was contracted to the American Car and Foundry Division of ACF Industries, Incorporated, under Contract DA-36-034-ORD-1423RD.

Scope of Investigation

4. The objective of this study was to determine the effects, if any, of rare-earth additions on the weldability of 1/2-inch armor steel. In its entirety, the investigation includes all pertinent phases of laboratory determinations and weldability, ballistic and explosion bulge tests concerned in the evaluation of three heats of manganese-molybdenum analysis wrought armor steel, one rare-earth-metal-treated, another rare-earth-oxide-treated and the third a normal production heat.

5. The work was divided into four phases:

A. The first phase covered the procurement of materials for test, the identification and cutting of the material, the preparation and evaluation of 3-, 4- and 5-inch patch diameter Navy circular patch test plates, cruciform tests for the determination of the relative crack sensitivity of the three materials, establishment of the technique and patch diameter for circular patch test plates of each material for explosion bulge testing, the preparation of circular patch plates, the preparation of straightaway butt welded and unwelded plates for explosion bulge testing, and the preparation of "H" plates for ballistic testing. The first phase is covered in Interim Report No. 1 (ACF Major Report 207).

Scope of Investigation (continued)

B. The second phase was concerned with the steel mill operating records and the laboratory phases of the investigation including chemical analyses, microstructure and microhardness studies, hardenability determinations, examination of gas cut edges for cracks and hardness, bend testing, impact testing (plate and weld deposit transition curves) and fatigue testing. Also, a sonic method of detecting cracks during and subsequent to welding was evaluated. This work was covered in Interim Report No. 2 (ACF Major Report 207A).

C. The third phase consisted of explosion bulge and ballistic testing of the plates produced in the first phase. The testing was carried out at Aberdeen Proving Ground and the results are included in Aberdeen Armor Test Report No. AD-1241.

D. The fourth and final phase is the evaluation of the weldability of the three types of armor based upon a correlation and interpretation of the results developed in the preceding phases of the work. This report is the fourth and concluding part of the project assigned to American Car and Foundry.

Plate Material

6. For the purposes of this investigation, Watertown Arsenal obtained from the Jones and Laughlin Steel Corporation three plates from each of three different heats of manganese-molybdenum-type wrought homogeneous armor steel representative of rare-earth-metal-treated, rare-earth-oxide-treated and normal production practices. The heats were identified as JL 0681, JL 0724 and JL 0823 respectively, and the three plates from each heat were a portion of the product of a single ingot early in the teeming (JL 0681, ingot 1; JL 0724, ingot 3; JL 0823, ingot 3). The plates were subsequently furnished to ACF as the material to be evaluated.

7. The scope of the investigation necessitated the procurement of additional plate material from each of the three armors involved. The additional armor was purchased directly from Jones and Laughlin by ACF and, in each case, was the product of the same ingot as the original government-furnished material.

8. Under Supplemental Agreement No. 1, three additional H plates were made from each heat and the material for the H plates was also purchased directly from Jones and Laughlin by ACF. However, no material was available from the originally selected ingots on two of the heats so the plate from heats JL 0681 and JL 0724 was taken from ingot 2. The plate from heat JL 0823 was again from the same ingot as the original government-furnished material.

9. Summarizing, the following plates were obtained for the investigation:

A. Plates from heat JL 0681 with rare-earth-metal addition:

1) * 3 plates 1/2" x 68" x 108" from ingot #1, cuts 1, 2 and 5.
2) ** 2 plates 1/2" x 68" x 108" from ingot #1, cuts 1 and 2.
3) *** 3 plates 1/2" x 37" x 42" from ingot #2, cut 1.

Plate Material (continued)

B. Plates from heat JL 0724 with rare-earth-oxide addition:

1) * 3 plates 1/2" x 57" x 196" from ingot #3, cuts 1, 2 and 5.
2) ** 1 plate 1/2" x 57" x 195-3/4" from ingot #3, cut 4.
3) *** 3 plates 1/2" x 37" x 42" from ingot #2, cut 4.

C. Plates from heat JL 0823, normal production armor:

1) * 3 plates 1/2" x 71" x 101-3/8" from ingot #3, cuts 1, 2 and 5.
2) ** 2 plates 1/2" x 71" x 101-3/8" from ingot #3, cuts 1 and 2.
3) *** 3 plates 1/2" x 37" x 42" from ingot #3, cut 3.

* Plates furnished by Watertown Arsenal.
** Plates purchased for original investigation.
*** Plates purchased for additional H plates.

10. The steel mill operating records furnished by Jones and Laughlin for the three heats involved are contained in Tables I, II and III. The rare-earth-metal additions were made to heat 0681 in the form of American Metallurgical Product's "Lanceramp No. 1" which has about 98% contained rare-earth metals, primarily cerium (45-50%) and lanthanum (30%). The rare-earth-oxide additions were made to heat 0724 in the form of the Molybdenum Corporation's "T" compound which is composed of about 83% rare-earth oxides with approximately 55% contained rare-earth metals, also primarily cerium and lanthanum. Both heats were treated with about the same weight (78.4 versus 71.5 pounds) of rare-earth metals.

11. The rare-earth-metal treated and rare-earth-oxide-treated heats were 50-ton heats whereas the normal production (also referred to in this report as untreated) armor was made as a 200-ton heat. There were differences in the methods of making slag, making furnace additions, blocking of the heat and making ladle additions, showing some variation between the heats in steel making practice. However, aside from the rare-earth additions, the most significant difference between the heats, according to the Jones and Laughlin mill records, appears to be that boron was added as a ladle addition to heats 0681 (Borosil) and 0823 (X-79 Grainal).

12. The Jones and Laughlin mill practice varies dependent upon the end application of the armor, particularly the final thickness, so that, while some of the variation in practice may be attributed to the different sizes of the heats and the fact that they were made at different times, the major difference is attributed to the apparent end use of heat 0724 for thinner plate, 1/2 inch or less.

13. The armor plate used in this study was heat treated by Jones and Laughlin in accordance with the normal production practices and met all requirements of MIL-A-12560 (ORD) at the mill.

Chemical Composition

14. The chemical compositions of the three heats, Table IV, were within the Jones and Laughlin declared range for their manganese-molybdenum armor except for a minor deviation; viz., the ladle analysis molybdenum for heat 0823 was .01% below the declared minimum. The rare-earth-oxide-treated heat, 0724, had a carbon content very

Chemical Composition (continued)

slightly below the normal and a medium manganese content. The rare-earth-metal-treated heat, 0681, had a higher carbon and manganese as did the top cut of the production heat. The bottom cut of the production heat showed a much lower carbon.

15. The sulfur in the oxide-treated and production heats was average (about .021%) but the sulfur content of the rare-earth-metal-treated heat (.012%) was significantly lower, even below the .014% minimum found in the last 86 Jones and Laughlin heats used by ACF. Since no hot metal samples were taken before the Lanceramp addition, it was not possible to definitely determine whether the rare-earth metals were a factor in reducing the sulfur content of the heat but it seems reasonable to assume that they were.

16. Although the mill operating records do not indicate that any boron was added to heat 0724, chemical analyses show that boron was present in armor from all three heats, including 0724, in amounts above the generally accepted minimum level of .0005% required to obtain the hardenability effects. Repeated wet analyses were made to check the boron in heat 0724 and close agreement was obtained in all analyses. Samples from all three heats were checked spectroscopically for boron and again boron was detected in each of the three heats in amounts agreeing with the analyses shown in Table IV.

Hardenability

17. Previous experiences in the fabrication of Army-type wrought homogeneous armor plate in the thinner sections have indicated that weldability, among other factors, is influenced to a large extent by the hardenability of the individual plate; further, that the hardenability in a given heat varies within fairly narrow limits but between different heats varies widely.

18. Since the armor plate was only 1/2 inch thick, it was not possible to use standard 1-inch Jominy end quench specimens for the hardenability determinations. The 1/2-inch substandard size specimen has been reliable for comparison purposes so the hardenability of the three heats was determined from the smaller specimens.

19. The hardenability curves, Figures 1, 2 and 3, indicate that the top cuts of heats 0681 and 0823 had the highest hardenabilities reflecting the higher carbon, manganese and molybdenum of heat 0681 as well as the higher carbon and higher manganese of the top cut of heat 0823. The hardenability of the rare-earth-oxide-treated heat was noticeably lower. Also, in each case, the hardenability of the bottom cut of the ingot was lower than that of the corresponding top cut. Only in the case of the bottom cut from heat 0823 was there a variation from the expected performance based on the chemical analyses; the specimens had a somewhat higher hardenability than would have been expected based on the lower carbon content.

20. It is to be noted that heat 0724 exhibited relative hardenability characteristics based upon its chemical analysis, compared to those of the other two heats, as though no boron had been added to the heat. With the boron content of each heat at a level sufficiently high to obtain hardenability improvement, the differences in hardenability between the three heats are greater than usual.

Impact Resistance

21. The impact strength of the plates from the three heats was determined at -40° F

Impact Resistance (continued)

(and down to -100° F) with Charpy V-notch specimens in accordance with the procedures outlined in MIL-A-12560 (ORD). The rare-earth-metal-treated heat, 0681, exceeded the minimum impact strength requirements of MIL-A-12560 (ORD) at -40° F whereas both of the other heats failed to meet the requirements of MIL-A-12560 (ORD) as stated or as modified by ECO 35140. The deviation from the specification requirement is shown in Figure 4 which illustrates the performance of the top and bottom cuts from each heat. The bottom cut in each case showed the higher impact strength in relation to the MIL-A-12560 requirement.

22. While manganese-molybdenum armor characteristically shows relatively low impact strength, heats 0724 and 0823 exhibited abnormally low impact strengths, even lower than the three foot-pound deviation permitted by Engineering Change Order 35140. The impact test results obtained in this investigation on individual plates are at variance with the mill reported impact strengths, all of which indicated that the heats passed the minimum specification requirements. This variation has not been explained and is not normally encountered. However, one point perhaps worthy of note is that the mill test reports and the heat 0681 values were determined on specimens in the high portion of the allowable hardness range, while the specimens from heats 0724 and 0823 were in the lower portion of the hardness range.

23. Ductility measurements made on the impact test specimens after they were broken indicated that all fractures down to the lowest temperature of test, -100° F, possessed some ductility. No completely brittle fractures were observed.

24. The impact strength of weld deposits in butt welds made with Tensilend 100 low hydrogen ferritic electrodes indicated that, at least down to -40° F, the impact strength of the weld deposit was greater than that of the base metal.

Gas Cutting

25. The test plates prepared in the course of this investigation were gas cut to size in accordance with an ACF standard procedure using the oxy-acetylene process. All edges were visually examined and the edges of several plates were magnafluxed but no edge cracking was detected.

26. The heat-affected zone hardness under the gas cut edge of each heat was studied on taper specimens. The highest maximum hardness and the greatest depth of high hardness were observed on heats 0681 and 0823. The maximum measured hardness was approximately 535 BHN. The maximum hardness attained on rare-earth-oxide-treated heat 0724 was substantially lower than for the other two heats; also, the depth of the zone of maximum hardness was only about two-thirds as great. The heat-affected zone pattern for the ingot top and bottom cuts within each heat were similar.

27. The hardness levels and hardness patterns on the three heats were in agreement with the results of the end quench hardenability tests. Heats 0681 and 0823 with the highest hardenabilities also exhibited the deepest heat-affected zones of greatest maximum hardness. Previous experimental work has indicated that edge hardnesses over 490 BHN are undesirably high for 1/2-inch armor gas cut by the ACF procedure, so that high and borderline hardenabilities of the rare-earth-metal-treated and production armor heats are indicated.

Welding

28. The weld joint design and welding procedure, Figure 5, used in the course of this investigation were in accordance with the ACF standard weld joint procedures for 1/2-inch Army-type wrought homogeneous armor plate. The joints were of the double-vee butt-type design with 45° included angles, 3/16-inch root gap and no land. Copper backup bars were used for all first-pass welds and the root pass was back-chipped before depositing welds on the back side.

29. The electrodes used were 5/32-inch and 1/4-inch diameter (3/16 inch in micro-hardness study only), low hydrogen, ferritic-type electrodes conforming to Specification MIL-E-986, Grade 230-15. Tensilend 100 electrodes were purchased from the Arcos Corporation from single lots per size in 10-pound sealed cans which were opened only as necessary. Once the cans were opened the unused electrodes were stored at 230° F until withdrawn for actual use.

30. The weldments made were produced by two welders qualified under the requirements of Specification MIL-W-12518. The welders had several years experience in the welding of Army-type armor and, in addition to production welding, had successfully produced a number of test weldments including H plates. The men are considered to be excellent welding operators who have proven by past performance that they are consistently capable of producing high quality weldments. In a further effort to reduce the effect of the welding operator variable, only the standard explosion bulge plates were prepared by both men; all other plates were welded by one welding operator.

Microstructure

31. The microstructures of the three heats consisted of typical tempered martensite with only minor variations in grain size and microstructure details. There was a difference in the amount of sulfide inclusions observed, correlating with the analyzed sulfur, but no significant difference in the type or shape of the sulfide inclusions was observed.

32. Microhardnesses were taken across 1/4-inch fillet welds made in one pass with 3/16-inch Tensilend 100 electrodes. The maximum hardness in the heat-affected zone was greatest for the specimen from rare-earth-metal-treated heat 0681, intermediate for production heat 0823 and lowest for rare-earth-oxide-treated heat 0724. The maximum hardnesses generally correlate with the maximum hardnesses in the heat-affected zones of gas cut plates and with the results of the end quench hardenability tests.

Cruciform Tests

33. Cruciform tests were made on the three armors as a test of their relative weldability; two cruciform test plates were made on each of the three materials. Cracks were found in the weld, fusion zone, heat-affected zone or plate material of each heat. The greatest concentration of cracks was in the last weld which is made under the greatest restraint.

34. The weldability of the armors was evaluated by sectioning the cruciform test plates at one-inch intervals and counting the number of sections which showed cracking. On this basis, it was indicated that the rare-earth-oxide-treated heat, 0724, had the best weldability and that the rare-earth-metal-treated and production armor heats were

Cruciform Tests (continued)

less weldable. The rare-earth-metal-treated heat, 0681, was rated slightly inferior to the untreated heat, 0823.

Circular Patch Test Plates

35. A series of Navy-type circular patch test plates (MIL-E-986A Ships) were made to determine the relative crack sensitivity of the armors; 3-inch, 4-inch and 5-inch diameter patches were made in 12" x 12" plates. The weldability of the rare-earth-oxide-treated armor, based on the frequency of cracking and the patch diameter, was clearly superior to that of the other two heats while the rare-earth-metal-treated armor and the production armor showed comparable weldability characteristics.

36. The 4-inch patch was selected as the optimum size for the preparation of circular patch explosion bulge test plates and nine 20" x 20" plates were prepared from each of the three materials. During the preparation of the circular patch explosion bulge test plates, cracking occurred in some plates from each armor, the incidence in the rare-earth-metal-treated heat being greater than for the other two steels. All weld metal defects were repaired and the plates before testing conformed to Radiographic Standard II of MIL-R-11468.

37. The circular patch plates were explosion bulge tested[(1)] at temperatures ranging from -90° F to 20° F with a 3-pound pentolite charge at a standoff distance of 24 inches. The average strain at 1-1/2 inches from the center of the patch is plotted against the testing temperature in Figure 6 and shows a clear difference between the oxide-treated heat and the other two heats. The rare-earth-oxide-treated plates exhibited acceptable ductility (above 1.0 percent strain) at all testing temperatures above -90° F. The one plate tested at -90° F indicated brittle behavior and the two plates tested at -70° F showed ductile behavior so the transition temperature has been taken at about -80° F.

38. The rare-earth-metal-treated heat and the production heat yielded rather mixed results but it is indicated that the transition temperature was at about -20° F.

39. Circular patch plates from all three heats cracked in a distinctive manner on explosion bulge testing. A typical fracture initiated in the fusion zone of the weld, propagated about an inch in either direction in the fusion zone and then progressed diagonally across the weld and into the base plate with little change in direction. From an examination of the extent of the plate cracking, it was possible to determine the FTE (fracture transition for elastic loading)[(2)], i.e., the highest temperature at which fracture occurs in the elastically stressed regions of the test plate (crack propagation out to the plate edges). The FTE for each type of armor was:

Steel	FTE, °F
Rare-earth-metal-treated	-20
Rare-earth-oxide-treated	-40
Untreated	-20

Thus from the standpoint of brittle crack propagation in the circular patch explosion bulge plates, the rare-earth-oxide-treated armor appeared to be the best of the three materials.

(1) The WELDING JOURNAL, October 1951, pp 499-s ff.
(2) The WELDING JOURNAL, June 1956, pp 275-s ff.

<u>Prime Armor Explosion Bulge Plates</u>

40. Twelve 20" x 20" plates of the heat treated virgin armor were furnished from each heat for explosion bulge test work. Two plates from each group were explosion bulge tested at about -130° F with a 3-pound charge and a standoff distance of 24 inches. Although three impacts were placed on each plate, no cracking resulted and maximum strain values of nearly 2% were realized.

41. Twenty-six of the prime armor plates were then modified with crack starters consisting of 1/2-inch holes drilled to one-half the plate thickness and filled with a hard surfacing weld metal. This type of crack starter produces the sharpest possible type of notch - a cleavage crack - at the beginning of the loading cycle and permits evaluation of the fracture characteristics of the steel loaded in the presence of the sharp notch.

42. From an examination of the extent of plate cracking in explosion bulge tests, the following FTE temperatures were determined (highest temperature permitting cracking out to the plate edges):

Steel	FTE, °F
Rare-earth-metal-treated	-40
Rare-earth-oxide-treated	-20
Untreated	-40

Thus from the standpoint of brittle crack propagation in the prime armor explosion bulge plates (with crack starters), the rare-earth-metal-treated and the untreated armors appear to be slightly better than the rare-earth-oxide-treated armor.

<u>Butt Welded Test Plates</u>

43. Twenty-four butt welded 20" x 20" explosion bulge test plates were fabricated from heats 0681 and 0724 and 28 plates were fabricated from heat 0823. Judged by the results of radiographic inspection, cracking occurred in 6 of the 24 plates from heat 0724 and on only one each of the 24 and 28 plates from heats 0681 and 0823 respectively. These results indicate that the weldability of the rare-earth-oxide-treated heat is inferior to that of the other two heats, a conclusion which is not entirely consistent with the results obtained in the welding of circular patch test plates where the rare-earth-metal-treated and the production heats showed comparable weldability but the rare-earth-oxide-treated heat showed superior weldability.

44. The butt welded plates were subsequently subjected to the explosion bulge test at Aberdeen Proving Ground using a 3-pound pentolite charge at a standoff distance of 24 inches. The results of the tests made with the weldments concave side up* are presented in Figure 7 and indicate a transition range of -60 to -115° F. Little or no difference was indicated between the three heats.

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*Footnote: Most of the butt welded explosion bulge test plates exhibited some "camber" (rotation about the weld axis) due to weld shrinkage. The initial explosion bulge tests were made with the concave side of the plate down since that side of the plate was prepared by removal of the weld reinforcement in the areas where the joint was to make contact with the die. After several plates had been tested, it was established that the amount of camber was greatly influencing the strain measurements. However, when duplicate test plates were selected - one with camber and one with little or no camber - and tested concave side <u>up</u>, the amount of camber had little or no effect. Thus the concave down results involve an uncontrolled variable and are not considered significant.

Butt Welded Test Plates (continued)

45. From an examination of the extent of the plate cracking, it was possible to determine the highest temperature permitting crack propagation out to the plate edges.

Steel	FTE, °F
Rare-earth-metal-treated	-70
Rare-earth-oxide-treated	-90 (no test made at -70° F)
Untreated	-70

Again the rare-earth-metal-treated and the untreated armors were indicated to be similar and possibly somewhat inferior to the rare-earth-oxide-treated armor. The differences between the FTE determined from the butt welded explosion bulge test data (-70 to -90° F) and the FTE's taken from the crack starter and circular patch tests (-20 to -40° F) may not be quite as great as indicated due to a lack of data in the butt welded explosion bulge test between -40 and -70° F. However, the consistency of the manner of failure of the butt welded explosion bulge plates at -40° F indicates a real difference between the FTE's of the butt welded explosion bulge and the other tests.

46. The fact that the FTE temperatures were lower in the butt welded explosion bulge test may be attributed to a less severe test condition for the base plate in the case of the butt welded explosion bulge test. With only two exceptions, the cracking in the butt welded explosion bulge plates, once initiated, extended from edge to edge of the plate whether the test was made above or below the FTE (edge-to-edge cracking confined entirely within the weld joint area is not considered to indicate the plate FTE). It would appear that there is some area within the heat-affected zone of the welded joint which is more susceptible to crack propagation than the base metal itself, even to temperatures below the FTE of the base metal as determined from the crack starter and circular patch explosion bulge tests. In the butt welded explosion bulge test, the initiated crack apparently can propagate easily to the edge without entering the plate while, in both the crack starter and circular patch explosion bulge plates, it is necessary that the crack propagate through the base metal to reach the plate edges.

47. A study was made of the average length of plate cracks at the testing temperatures for the plates fired with the concave side up and the data are plotted in Figure 8. The lower limit of the transition zone is fairly sharply defined at about -100° F. Again there appears to be no significant difference between the relative performance of the three heats.

H Plates

48. Twelve H-welded plates, 4 from each heat, were prepared for ballistic testing. On an over-all basis and judging weldability in terms of cracking encountered in fabrication, the rare-earth-oxide-treated heat appeared to be slightly better than the rare-earth-metal-treated heat and both seemed to be more readily weldable than the production armor. One plate from each heat caused an unusual and unexplained amount of difficulty in obtaining radiographically sound welds. No unusual significance is attached to this condition since every effort was made to produce the plates at random under identical conditions.

49. The plates were ballistically tested at Aberdeen by the procedure outlined in MIL-W-12518 (ORD) except that tests were made at -40° F, 0° F, 40° F and 52° F rather

H Plates (continued)

than only at ambient. The leg welds were struck with 37mm H.E. M54 shell and each plate was repeatedly tested within the limitations imposed by the extent of cracking in the previous round. The twelve plates were struck with a total of 37 rounds.

50. A preliminary review of the cracking data immediately pointed up the fact that the occurrence of cracking was influenced by the distance of the center of impact from the weld:

Distance from center of impact to weld, inches	Crack occurrence
0 (on weld)	21 in 21 impacts
1/2	5 in 6 impacts
3/4	2 in 3 impacts
1	1 in 3 impacts
over 1 to 1-3/4	1 in 4 impacts

The trend was not affected by the testing temperature, the grade of armor or the number of the impact (whether the first, second or third) so it appears that the results from impacts lying one inch or more from the weld should be disregarded.

51. The average of the cracking produced by the rounds fired against each H plate (excluding those rounds one inch or more off target) is represented graphically in Figure 9. At ambient temperature (40° F and 52° F), the test results indicate the rare-earth-metal-treated armor to be the best with the oxide-treated armor meeting the specification limit at 52° F but failing due to excessive leg cracking at 40° F and the untreated armor failing at both temperatures. At 0° F the metal-treated armor failed, the oxide-treated armor passed and the untreated armor was disqualified (and designated as an "unfair test") due to "excessive" base metal cracking. At -40° F both rare-earth-treated armors were disqualified as unfair tests while the untreated armor failed due to excessive leg cracking.

52. Thus, based on average results obtained from 12 H plates with 30 rounds striking within one inch of the weld, the H plate provided neither consistent nor significant trends. Moreover, 3 of the plates were disqualified as unfair tests. With regard to the unfair tests, it is of interest to note that the crack starter and circular patch explosion bulge FTE temperatures could have been used to predict the temperatures producing excessive base metal cracking in the H plates.

Other Tests

53. Two other series of tests were made to assist in an evaluation of the material performance. A series of bend tests were made on the base armor and it was indicated that the rare-earth-oxide-treated heat could be cold formed with greater elongation than either of the other two heats. It was also determined that the elongation to failure in cold bending was lower for the bottom cuts of the ingots than for the top cuts.

54. Limited fatigue testing was conducted on fillet welded joints in the three armor steels. The test procedure involved tensile loading at the toe of fillet welds in cantilever-type specimens. The data were too limited to draw any general conclusions

Other Tests (continued)

but there was a trend indicating that the endurance strength of the specimen was proportional to the tensile strength and hardenability of the base material.

Discussion

55. The selection of criteria for defining the weldability of any given material has long been a subject for controversy and no widespread acceptance of any single standard or set of standards has been attained. In particular, a number of tests have been considered for determining the weldability of Army-type armor but none has yet been found which provides the sensitivity or reliability necessary with such a borderline material. Such specimens as the H plate, the circular patch plate, the slotted plate and the cruciform specimen have been considered and each serves a useful purpose in specific instances but has not been adopted as universally applicable.

56. Therefore, the weldability of the three armor steels studied in the course of this investigation must be judged on a comparison basis with the background of the factors known to influence the production of an armor structure. The selection of such factors is empirical but has proven to be reasonably reliable in predicting the relative weldability in production applications.

57. The first factor to be considered in evaluating the weldability of the three steels is the probability of producing a sound weldment. The experience in preparing the circular patch explosion bulge plates, the butt welded explosion bulge plates and the H plates provides a range of weldments with differing degrees of restraint. The rare-earth-oxide-treated heat was clearly less sensitive to cracks than the other two heats in the preparation of the circular patch test and circular patch explosion bulge plates. Conversely, more cracking was obtained in the rare-earth-oxide-treated heat in the preparation of the butt welded explosion bulge plates. Finally, in the case of the H plates, the rare-earth-oxide-treated heat demonstrated a very slight superiority.

58. In all three instances, the rare-earth-metal-treated and the production heats showed comparable weldability and, by attaching greater weight to performance in the preparation of the highly restrained circular patch test plates, the rare-earth-oxide-treated heat is judged to have better weldability.

59. Experience with the cruciform test has been limited but in a few instances it has distinguished between crack-sensitive heats of manganese-molybdenum armor and those which are less prone to cracking. The cruciform tests conducted in the course of this investigation did not demonstrate that any of the armors possessed superior weldability but it was indicated that the rare-earth-oxide-treated heat was the best of the three. The rare-earth-metal-treated and production heats were generally comparable although the production heat was judged to be somewhat better than the rare-earth-metal-treated heat.

60. Another factor which is commonly used to judge the weldability of Army-type armor is the hardenability of the steel. Assuming that the armor plate successfully meets the requirements of the applicable material specifications, the armor with the highest hardenability is almost invariably the most crack-sensitive material. In this study the rare-earth-metal-treated and production armor heats possessed clearly higher hardenabilities than did the rare-earth-oxide-treated heat. The differences in hardenability were borne out by microhardnesses in heat-affected zones and the hardnesses

Discussion (continued)

in the heat-affected zones remaining after oxy-acetylene cutting. Thus, on the basis of hardenability, experience indicates that the rare-earth-oxide-treated heat should be the most easily welded heat in a production application, a conclusion which is borne out by the results of the cruciform test and the preparation of the welded plates.

61. Provided a sound weldment can be produced, weldability is also measured by the suitability of the welded structure for the intended application which, in the case of armor plate, means that the structure must be resistant to shock loading. The resistance to shock loading has been measured here by laboratory impact tests, by firing tests and by explosion bulge testing.

62. The impact strength of the three Army-type armor steels, measured by breaking Charpy V-notch specimens, was characteristically low. The rare-earth-metal-treated armor was the only one which passed the impact resistance requirements of MIL-A-12560, while the remaining two heats showed comparable and substantially lower impact resistance based on the specification requirements. However, the test specimens exhibited some ductility in all fractures and none broke in a completely brittle manner.

63. The standard method for evaluating the specific welding procedure for a welded armor structure is the H plate ballistic test. The test is not highly discriminating and the results are difficult to interpret constructively, but it has been widely used and is the best service-type test on which background information is available. Had the H plates been considered as qualification plates where only the first round impact (within 1-3/4 inches of the weld) at ambient temperature is used in the rating, the rare-earth-oxide steel plate would have been classed as the best of the three armors. The production heat which failed at both 40° F and 52° F would have been classed as the least desirable. However, after repeatedly firing the H plates, the apparent differences between the three heats disappeared and, on the basis of total cracking, there was no significant and consistent difference between the performance of H plates made from the test armors.

64. The H plate ballistic tests made in the course of this study confirm the lack of preciseness and the nondiscriminatory nature of the test as presently conducted and evaluated. If the test is to be used in the future, it is indicated that the following changes in MIL-W-12518 (ORD) are desirable:

A. The presently allowable off-center impact distance of 1-3/4 inches is excessive and should be reduced to less than 1 inch.

B. Tests should be made at least in duplicate.

C. Extensive plate cracking should be recognized as a natural phenomenon indicating that the armor (at the temperature of test) is as brittle as, if not more brittle than, the weld joint itself.

65. From the results of the crack-starter explosion bulge tests on the prime armor plate, it was indicated that the rare-earth-metal-treated heat and the untreated heat were somewhat superior to the oxide-treated heat in resistance to brittle crack propagation. Without crack starters, all three armor steels showed acceptable ductility and strain distribution.

Discussion (continued)

66. The circular patch plate explosion bulge testing showed a clear difference in the ductile-to-brittle transition between the rare-earth-oxide-treated and the other two heats. The oxide-treated plates showed a transition to brittle behavior at about -80° F while the metal-treated and untreated heats exhibited transitions at about -20° F. The same trend was shown by the FTE's although the difference between the temperatures was somewhat reduced.

67. No clear distinction between heats was evident in the butt welded explosion bulge plates where the ductile-to-brittle transition occurred in the range of -60 to -115° F. It is interesting to note that the FTE's determined from the butt welded explosion bulge plate test results (-70 and -90° F) lie within this transition range. No significant differences between the three heats were observed.

68. Treatment of cast steel with rare earths has been reported to improve the impact resistance of the steel. The rare-earth-metal-treated heat exhibited the best impact resistance in the Charpy V-notch test whereas the rare-earth-oxide-treated and production steels were comparable at lower values. The rare-earth additions apparently did not adversely affect the impact resistance of the armor and it is possible that the metal addition actually improved the impact strength. The significance of the differences in the laboratory impact tests is decreased, however, since the rare-earth-metal-treated heat did not exhibit improved performance in the explosion bulge and firing tests. The rare-earth-metal-treated heat did show a somewhat superior resistance to crack propagation in the prime plate tests but again this was partially counterbalanced by extensive plate cracking in the firing tests at -40° F.

69. In an evaluation of the relative weldability of the rare-earth-treated heats, it was intended that a comparison should be made with the production heat included in the study. The work performed does not indicate a clear over-all superiority of any one of the three armor steels; however, the two rare-earth-treated heats were equal to or better than the production armor in all of the tests performed. The rare-earth-metal-treated steel showed a higher impact resistance and a greater resistance to crack propagation in the prime armor but the rare-earth-oxide-treated heat exhibited the best properties in several of the fabrication- and service-type tests. The rare-earth-oxide-treated heat is, therefore, judged to possess slightly better weldability characteristics than the rare-earth-metal-treated heat which is in turn considered to be at least the equal of the production armor.

70. The difference in weldability, primarily from the standpoint of fabrication, is believed to be closely associated with the hardenability of the base material and it has not been possible to distinguish between attributes and characteristics which are influenced by the rare-earth additions and those controlled by hardenability. The fabrication performance of the rare-earth-oxide-treated heat was the best but its hardenability was also the lowest which in itself indicates that no serious difficulty should be encountered in fabrication. The evidence tends to indicate that the hardenability of the base materials was controlled by the chemical analysis and not by the rare-earth additions so that, except in the possible single case of the higher impact strength of the rare-earth-metal-treated heat, it does not appear that the rare-earth additions in themselves had any significant effect upon either the hardenability or the weldability in fabrication.

Table I

Mill Operating Record
Rare-Earth-Metal-Treated Heat 0681

Open hearth charge:
- 50,000 lbs heavy melting molybdenum scrap
- 40,000 lbs cold pig iron

Flux charge:
- 5,100 lbs limestone
- 2,600 lbs burnt lime

Furnace additions:
- 1,000 lbs burnt lime
- 300 lbs fluorospar
- 180 lbs molybdic oxide
- 750 lbs ore

Furnace block:
- 1,450 lbs silico-manganese
- 850 lbs 11% ferro-silicon
- 850 lbs ferro-manganese

Ladle additions:
- 120 lbs calcium-silicide
- 80 lbs Lanceramp
- 72 lbs aluminum
- 60 lbs borosil

The heat was poured into 27" x 52" big end up hot-topped molds and the ingots were rolled into 46" x 4" slabs which were slow cooled from 1750° F to 600° F in 76 hours and were then conditioned by flame scarfing at 300° F to 600° F.

Heat treatment:

Austenitizing furnace	1/2 hour hold at 1650° F water quench
Tempering furnace	1-1/4 hours hold at 875° F water quench

Table II

Mill Operating Record
Rare-Earth-Oxide-Treated Heat 0724

Open hearth charge:
- 50,000 lbs heavy melting molybdenum scrap
- 40,000 lbs cold pig iron

Flux charge:
- 5,100 lbs limestone
- 300 lbs burnt lime

Furnace additions:
- 400 lbs burnt lime
- 700 lbs fluorospar
- 480 lbs molybdic oxide

Furnace block:
- 300 lbs 11% ferro-silicon
- 250 lbs silico-manganese
- 2,250 lbs ferro-manganese

Ladle additions:
- 200 lbs ferro-manganese
- 130 lbs rare-earth oxide (T compound)
- 80 lbs 50% ferro-silicon
- 400 lbs alsifer

The heat was poured into 27" x 52" big end up hot-topped molds and the ingots were rolled into 48-1/2" x 4-1/2" slabs which were slow cooled from 1550° F to 600° F in 72 hours and were then conditioned by flame scarfing at 300° F to 600° F.

Heat treatment:

Austenitizing furnace	1/2 hour hold at 1650° F water quench
Tempering furnace	1-1/4 hours hold at 850° F water quench

Table III

Mill Operating Record
Untreated Heat 0823

Open hearth charge:
- 170,000 lbs heavy melting molybdenum scrap
- 38,000 lbs ore
- 223,000 lbs hot metal

Flux charge:
- 25,600 lbs limestone

Furnace additions:
- 8,100 lbs burnt lime
- 11,000 lbs scale
- 1,200 lbs molybdenum as molybdic oxide
- 20,000 lbs iron jigger (1 hour prior to block)

Residual alloys:

.16% Mo	.04% Cu
.02% Ni	.02% Cr

Furnace block:
- 1,000 lbs silico-manganese
- 1,200 lbs 11% ferro-silicon
- 8,500 lbs ferro-manganese
- (heat blocked at 2915° F - .09% C)

Ladle additions:
- 350 lbs medium carbon-manganese
- 1,000 lbs regular manganese
- 720 lbs X-79 Grainal
- 1,100 lbs alsifer

The heat was poured into 27" x 50" big end up hot-topped molds and the ingots were rolled into 48" x 4-1/2", 43-1/2" x 4", and 38-1/2" x 4" slabs. The slabs were slow cooled from 1370° F to 650° F in 78 hours and were conditioned by flame scarfing at 300° F to 600° F.

Heat treatment:

Austenitizing furnace	1/2 hour hold at 1650° F water quench
Tempering furnace	1-1/4 hours hold at 860° F water quench

Table IV

Chemical Analyses
in %

Heat	Ingot	Cut	TC	Mn	P	S	Si	Ni	Cr	Mo	B
JL 0681*	Ladle		0.30	1.63	.016	.013	0.29	ND	ND	0.44	
JL 0681	1	1	0.32	1.70	.014	.014	0.26	0.02	0.05	0.47	.0020
JL 0681	1	5	0.29	1.66	.015	.010	0.28	0.02	0.05	0.46	
JL 0724*	Ladle		0.25	1.53	.010	.022	0.20	ND	ND	0.44	
JL 0724	3	1	0.27	1.59	.012	.024	0.15	0.03	0.02	0.46	
JL 0724	3	5	0.25	1.58	.013	.019	0.18	0.03	0.03	0.44	.0025
JL 0823*	Ladle		0.27	1.68	.020	.023	0.20	ND	ND	0.39	
JL 0823	3	1	0.30	1.71	.020	.024	0.17	0.01	0.03	0.40	.0010
JL 0823	3	5	0.23	1.66	0.17	.018	0.18	0.01	0.02	0.42	
J&L established range, 1/4" to 3/4" incl.			.22 / .32	1.45 / 1.85	.04 max.	.04 max.	.10 / .30			.40 / .55	

* Jones and Laughlin analyses.
ND Not determined.

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 48 T)

DATE 5-17-54
LABORATORY ACF
TYPE SPECIMEN 1/2" D (SAE)
TEST NO.

TYPE	HEAT NO	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo		[illegible]	[illegible]
ARMOR	JL 0681		.32	1.70	.014	.014	.26	.02	.05	.47		1650	1625
	ING. I CUT I												
ARMOR	JL 0681		.29	1.66	.015	.010	.28	.02	.05	.46		1650	1625
	ING. I CUT 5												

REMARKS:

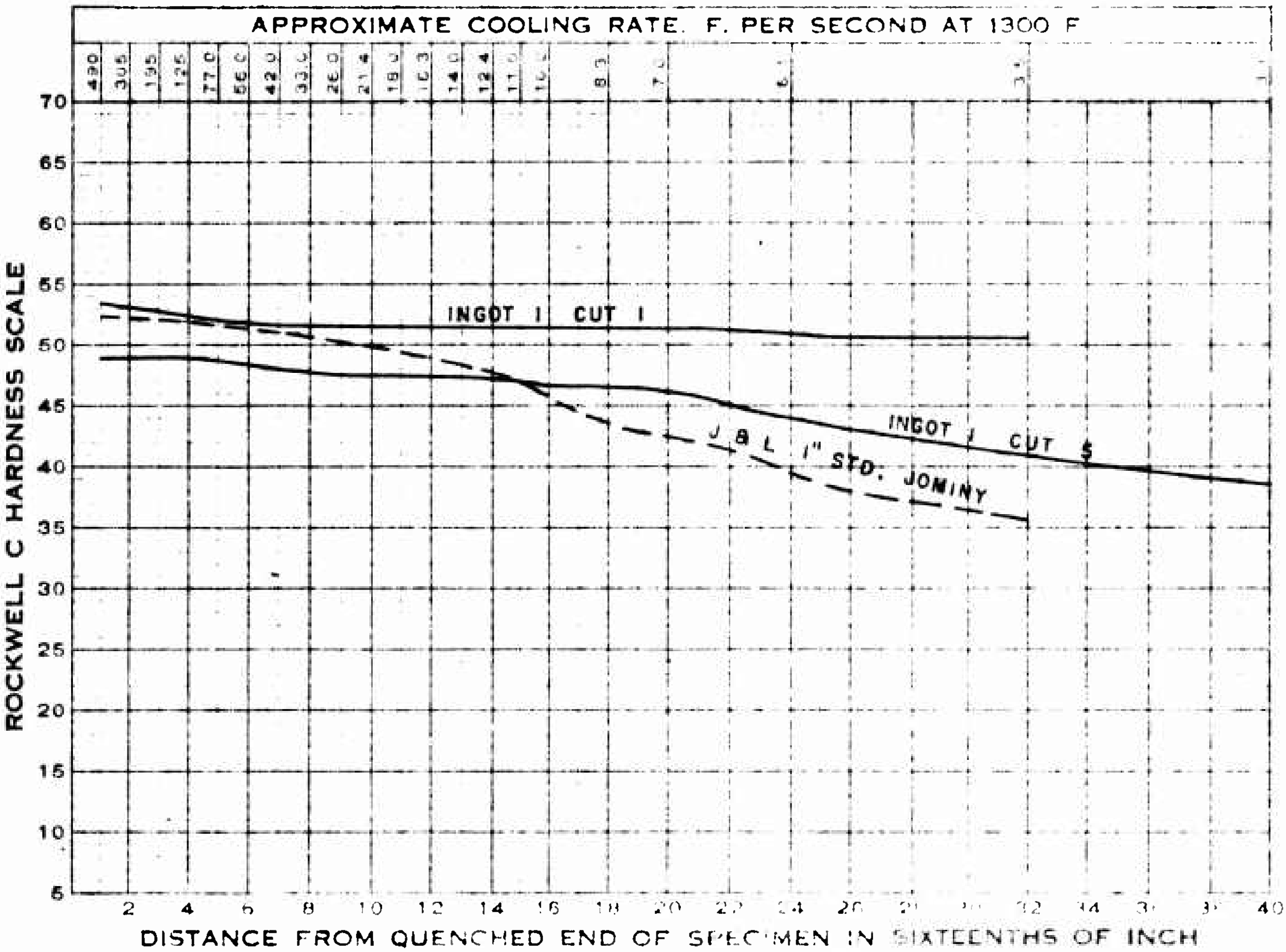


Figure I
END QUENCH HARDENABILITY DATA
HEAT JL 0681

MR 2078

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 48 T)

DATE 5-17-54
LAB. MATERIAL ACF
TYPE SPECIMEN 1/2" D (SAE)
TEST NO.

TYPE	HEAT NO.	GRAIN SIZE	C	Mn	P	S	Si	Ni	Cr	Mo			
ARMOR	JL 0724		.27	1.59	.012	.024	.15	.03	.02	.46		1650	1625
	ING 3 CUT 1												
ARMOR	JL 0724		.25	1.58	.013	.019	.18	.03	.03	.44		1650	1625
	ING 3 CUT 5												

REMARKS:

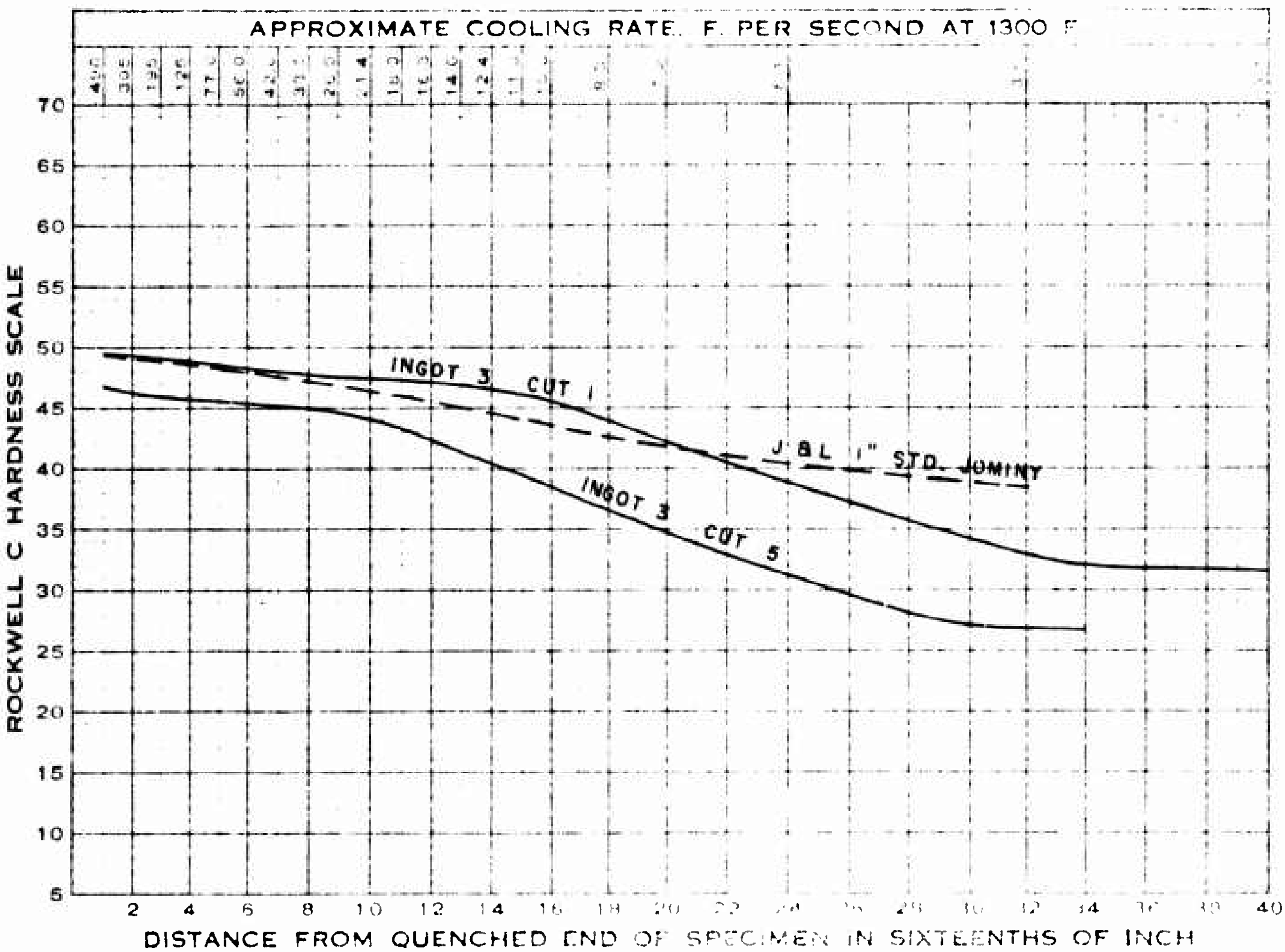


Figure 2
END QUENCH HARDENABILITY DATA
HEAT JL 0724

A. S. T. M. END QUENCH TEST
FOR HARDENABILITY
OF STEEL (A 255 - 48 T)

DATE 5-17-54
ACF
1/2" D (SAE)

TYPE	HEAT NO	[illegible]	C	Mn	P	S	Si	Ni	Cr	Mo		[illegible]	[illegible]
ARMOR	JL 0823		.30	1.71	.020	.024	.17	.01	.03	.40		1650	1625
	ING. 3 CUT 1												
ARMOR	JL 0823		.23	1.66	.017	.018	.18	.01	.02	.42		1650	1625
	ING. 3 CUT 5												

REMARKS:

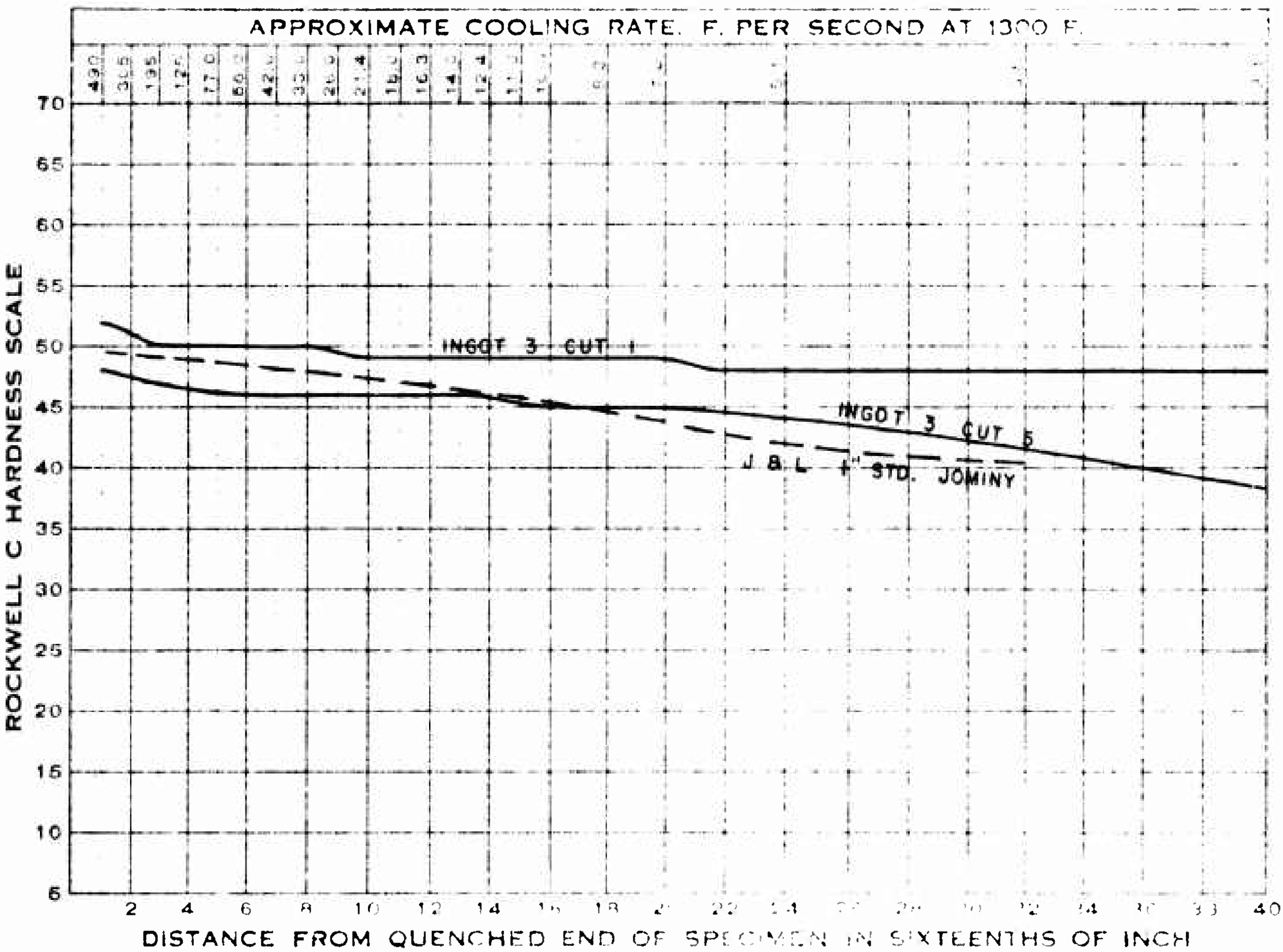
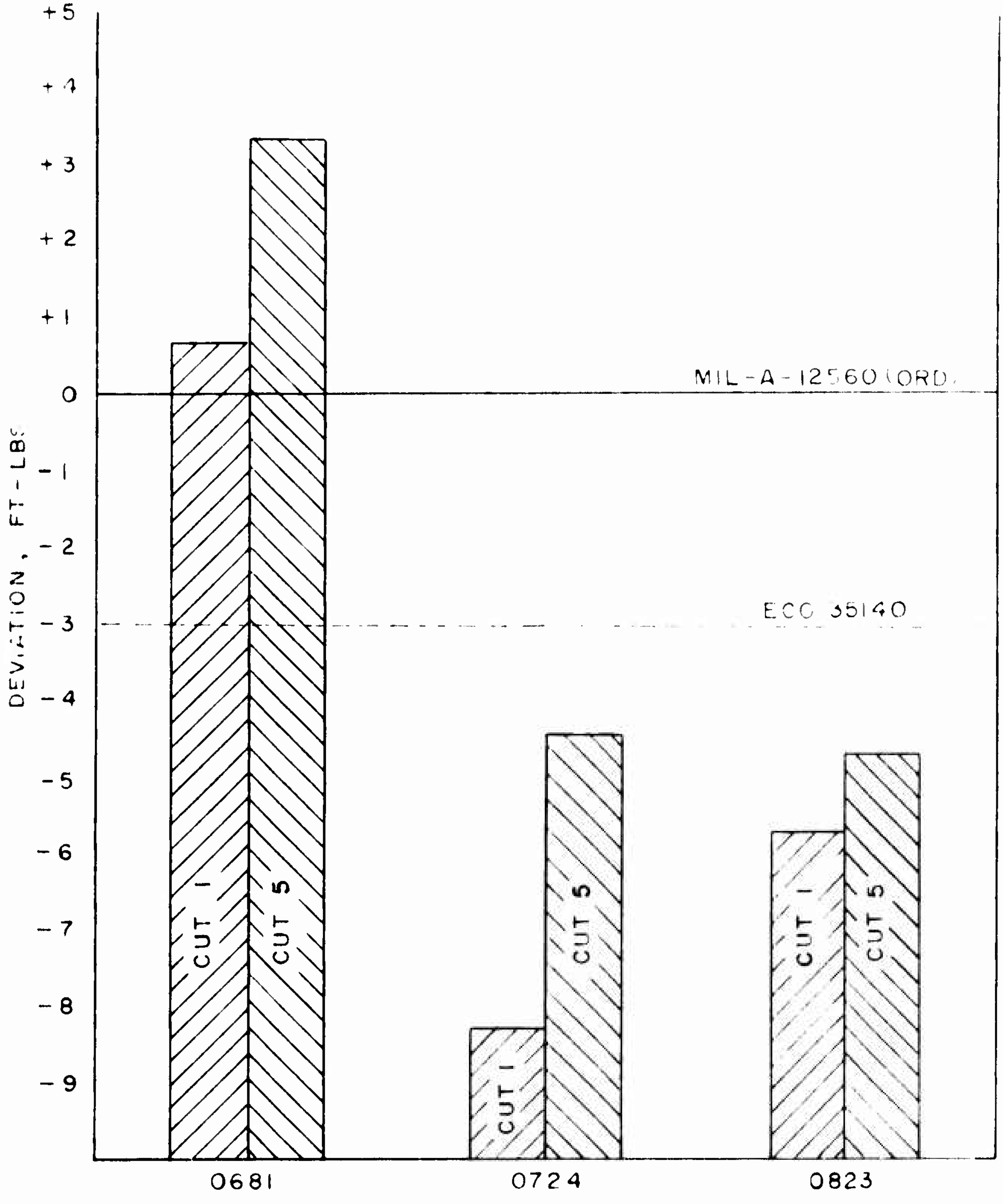


Figure 3
END QUENCH HARDENABILITY DATA
HEAT JL 0823



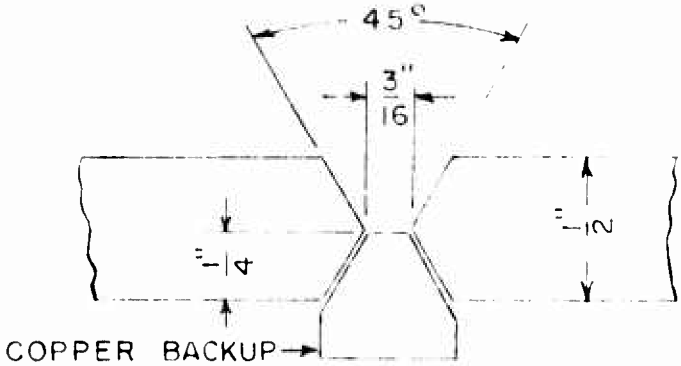
IMPACT STRENGTH

DEVIATION FROM MINIMUM REQUIREMENTS OF MIL-A-12560
CHARPY V-NOTCH AT -40°F

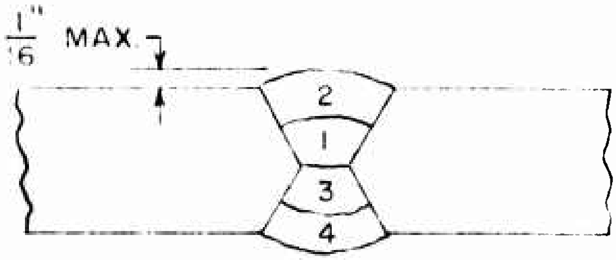
MR 207 B

AMERICAN CAR AND FOUNDRY DIVISION
RESEARCH AND DEVELOPMENT DEPARTMENT

Figure 4



JOINT DIMENSIONS



PASS SEQUENCE

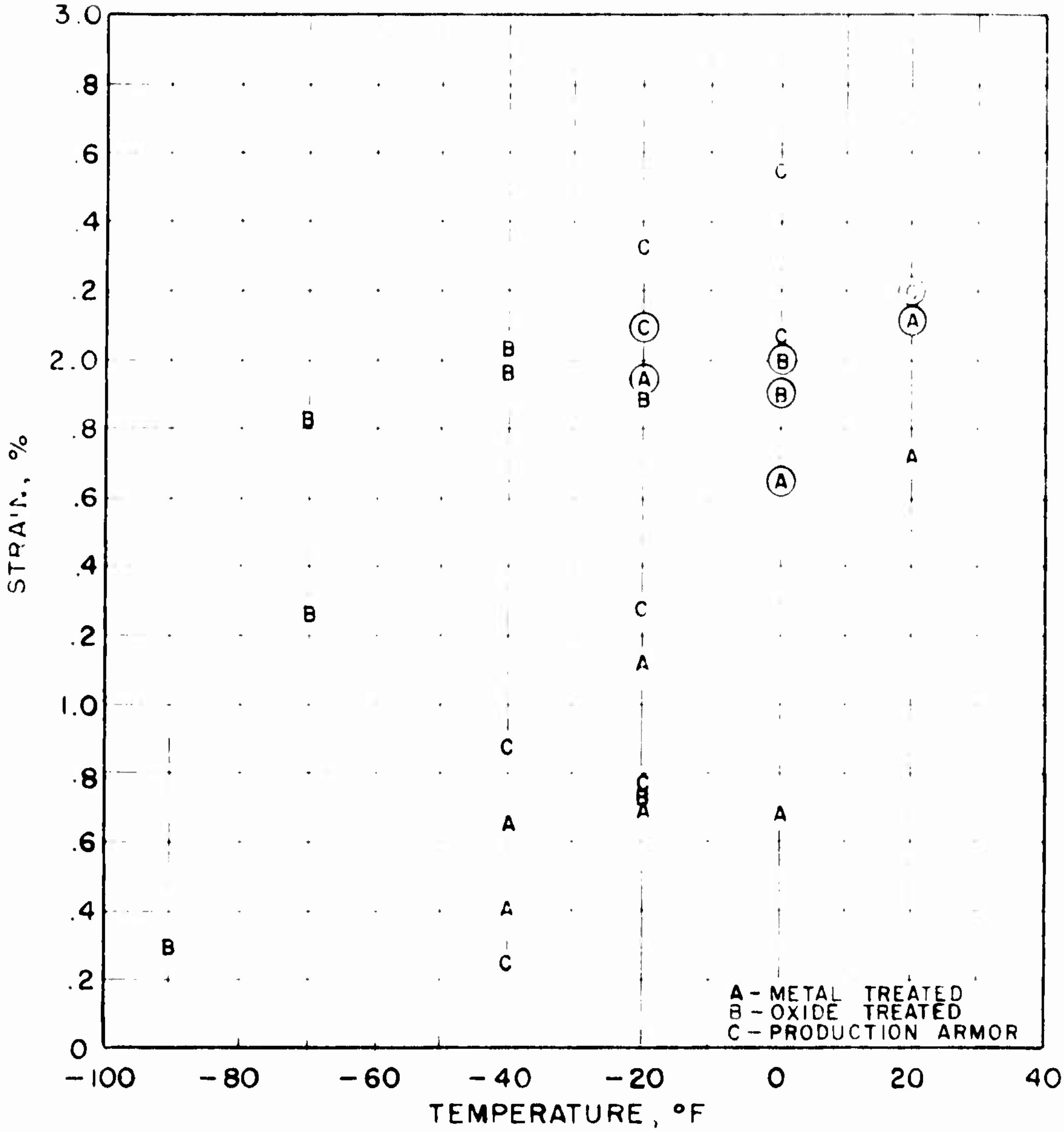
PASS	DIA. ROD	AMPS	VOLTS	TYPE OF PASS
1	5/32	170	23	BEAD
2	1/4	290	24	BEAD
3	5/32	170	23	BEAD
4	1/4	290	24	BEAD

JOINT DESIGN AND WELDING PROCEDURE

MR 207 B

ACF INDUSTRIES, INCORPORATED
RESEARCH AND DEVELOPMENT DEPARTMENT

Figure 5



AVERAGE STRAIN IN CIRCULAR PATCH PLATES

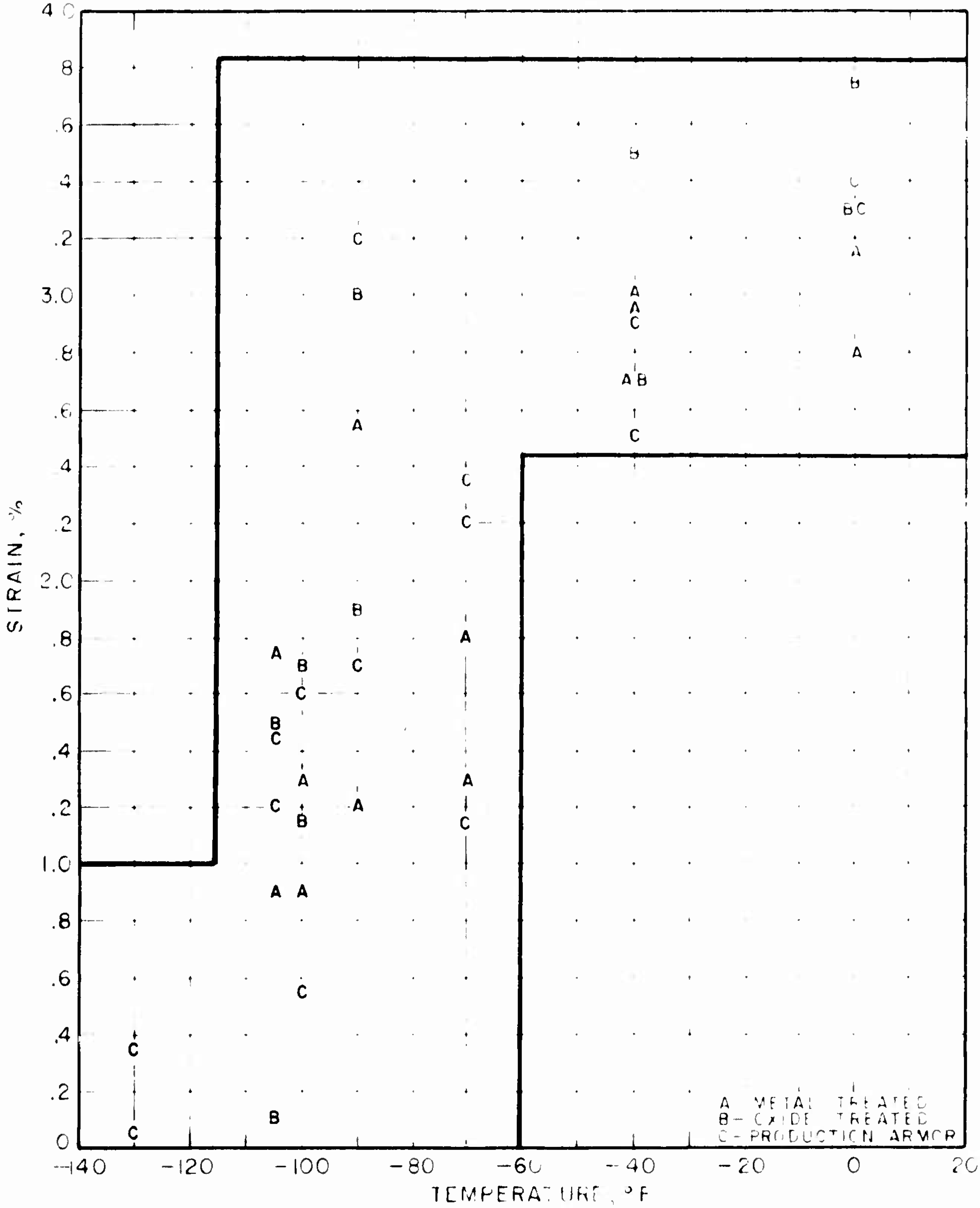
AT $1\frac{1}{2}$" - O INDICATES NO CRACKING

FROM APG REPORT AD-1241

MR 207 B

AMERICAN CAR AND FOUNDRY DIVISION
RESEARCH AND DEVELOPMENT DEPARTMENT

Figure 6



AVERAGE STRAIN IN BUTT WELDED PLATES

TESTED WITH CONCAVE SIDE UP

FROM APG REPORT AD-1241

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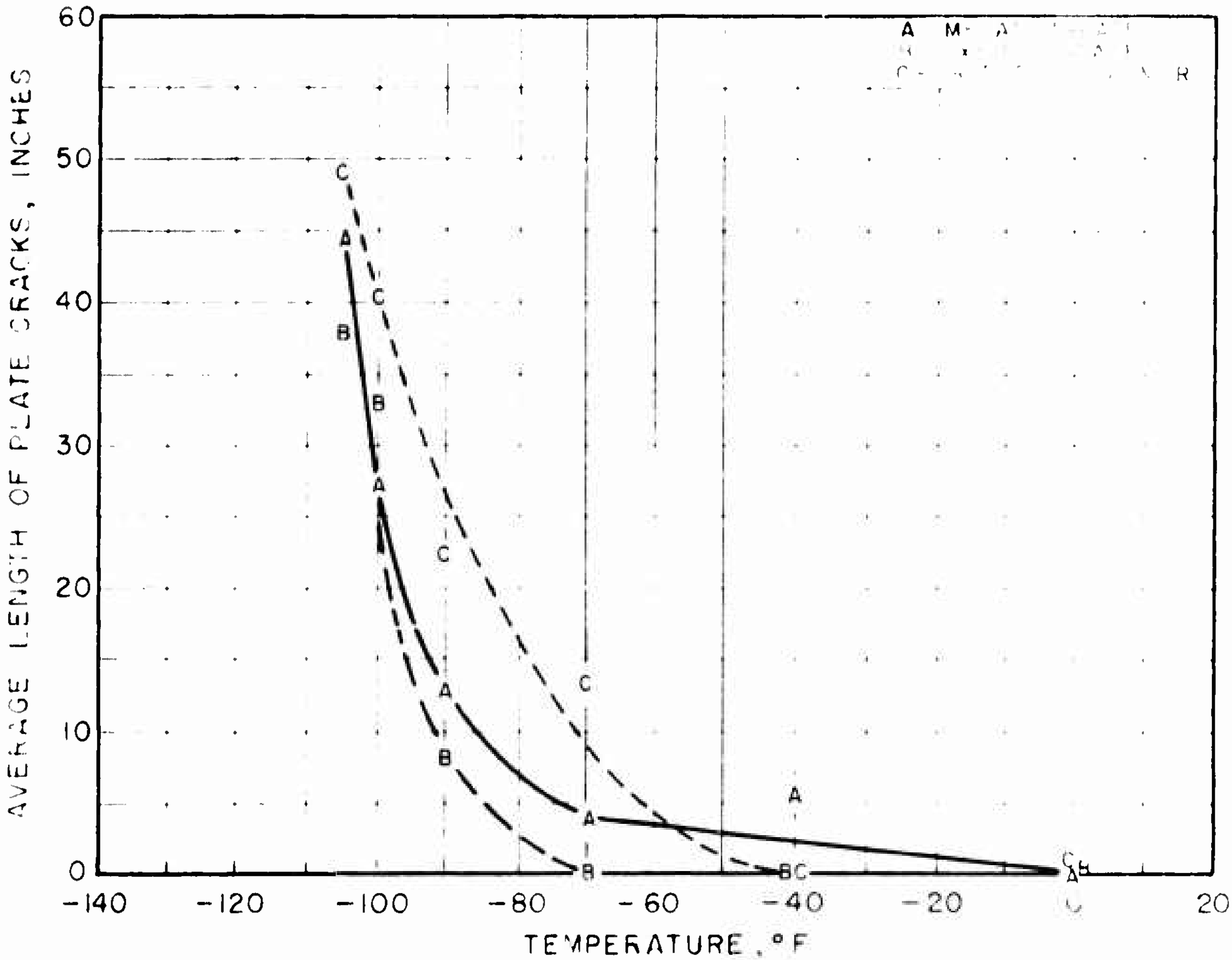
RESEARCH AND DEVELOPMENT DEPARTMENT

Figure 7



AVERAGE LENGTH OF PLATE CRACKS

BUTT WELDED PLATES TESTED WITH CONCAVE SIDE UP
FROM APG REPORT AD-1241

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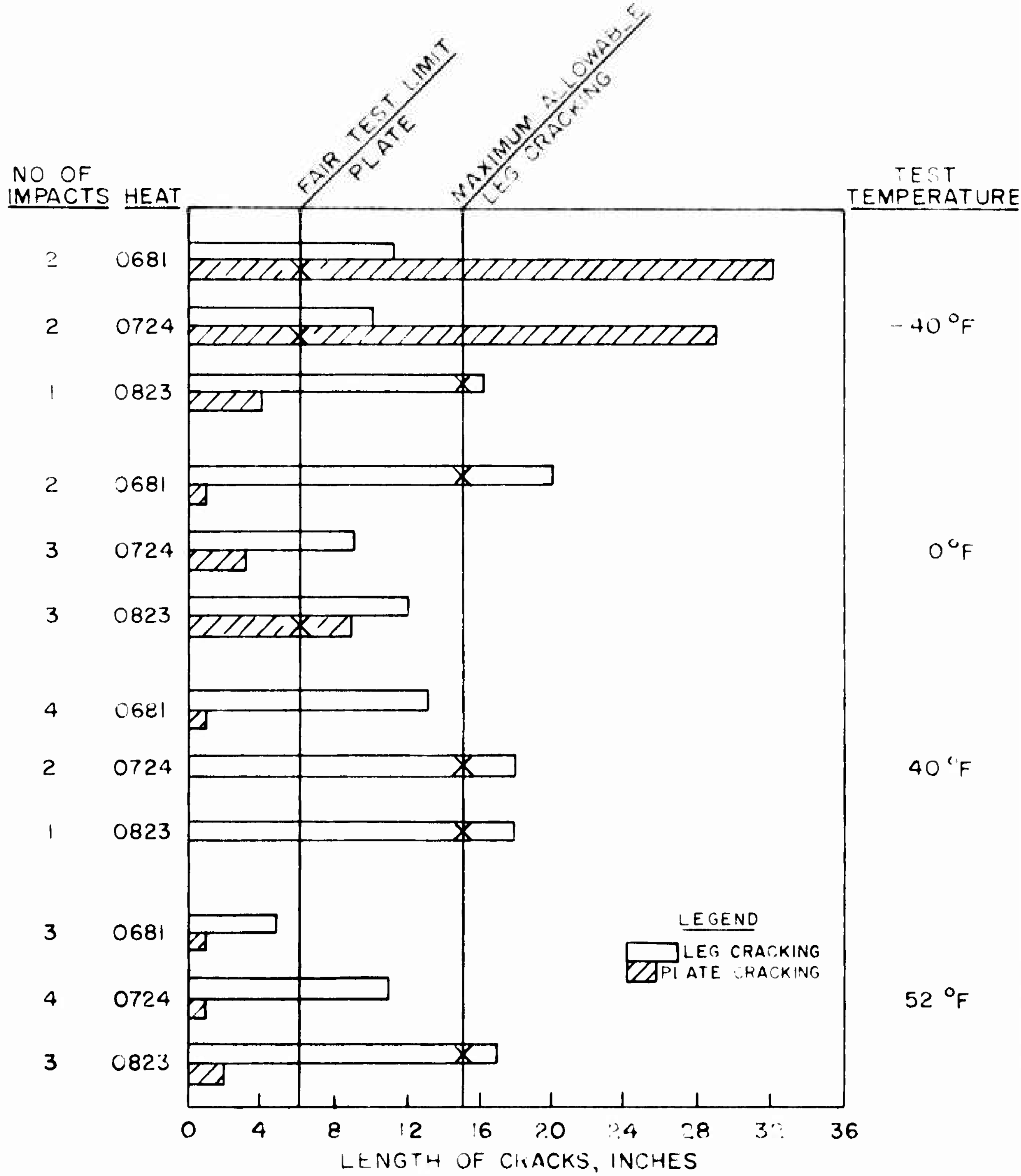
Figure 8



AVERAGE CRACKING IN H PLATES
FOR IMPACTS WITHIN 1" OF WELD
FROM APG REPORT AD-1241

FT
LH
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Figure 9